MAKING PROCESS
PLANTS INHERENTLY SAFER

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This article is based on a paper presented at the American Institute of Chemical Engineers 2011 Spring Meeting and 7th Global Congress on Process Safety, Chicago, IL, Mar. 13–16, and the subsequent article "Make Your Existing Plant Inherently Safer," by V. H. Edwards and J. Chosnek, Chemical Engineering Progress, 108 (1), pp. 48–52, Jan. 2012.

Inherently safer design (ISD) methods have matured during the past decade. Making process plants inherently safer has obvious advantages and is easiest to do when designing a new plant. Many older plants currently in operation were designed and built without the benefits of ISD. Inherently safer design reviews of these existing plants and their associated supply chains may identify opportunities for improvements, permit life cycle cost-benefit evaluations of the potential improvements, and sometimes allow improvements to be made during scheduled maintenance. This paper outlines methods to conduct an inherently safer design review of an existing plant and concludes with several examples of successful modifications of existing plants.

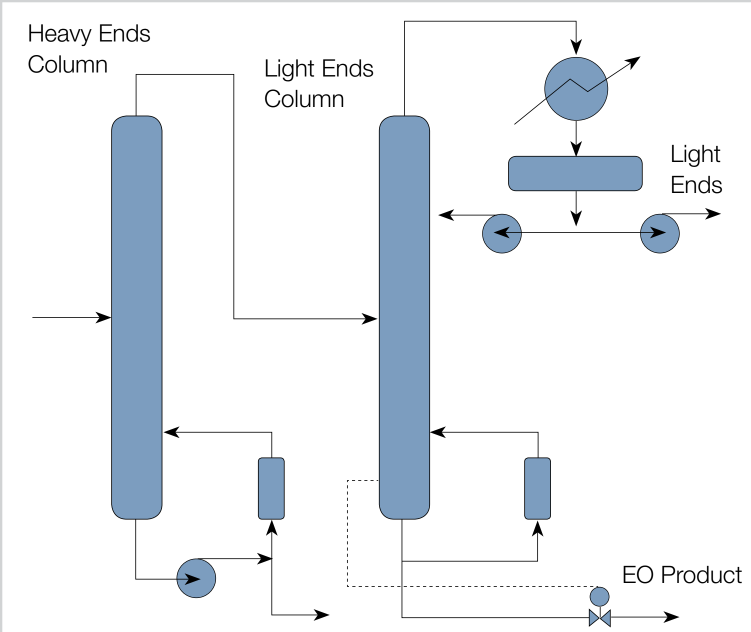

Figure 1. *Original process*

WHAT IS INHERENTLY SAFER DESIGN?

In 1974, loss of containment at a Nylon intermediates plant in Flixborough, England, released an estimated 50 tons of hot cyclohexane, forming a large flammable vapor cloud. The cloud exploded, killing 28 people and injuring many others. The plant was destroyed and never reopened. This tragic incident prompted Trevor Kletz to begin the creation of inherently safer design (ISD) or inherently safer technology (IST). His response was a paper entitled "What you don't have can't leak." Since then, ISD has developed under the leadership of Kletz and others to become one of the foundations of process safety engineering [1, 2].

The four key strategies of ISD are:

- Minimize – Use smaller inventories of hazardous substances
- Substitute – Replace a hazardous substance with a less hazardous substance
- Moderate – Reduce the hazards by employing milder temperatures, pressures and other process conditions
- Simplify - Design the process to reduce the potential for, or consequences of, human error, equipment failure, or intentional harm

An inherently safer design (ISD) will totally eliminate some hazards and reduce others resulting in a safer plant [1]. But is it appropriate or economical? When a hazard has been eliminated or its frequency of occurrence reduced, as intended by ISD, the instrumentation and procedures used to control the hazard are no longer necessary. Depending on the nature of these controls, their life cycle costs can be significant in terms of the expertise and time required for maintenance. Besides, even the best designed and maintained controls can fail, potentially leading to an incident and the resulting loss.

WHY CONSIDER INHERENTLY SAFER DESIGN FOR EXISTING PLANTS?

Most currently operating plants in the United States were designed and built prior to the 1990s. In those days engineers tended to design with more "fat" because instrumentation and controls were not that sophisticated, computer modeling was less prevalent, and instrumentation costs were a smaller percentage of total installed cost than they are today. This over-design turned out to be a boon in the years following the initial design because plants could increase capacity with little investment.

Unfortunately, the end result was that plants started running close to their design limits, reducing safety margins and increasing the probabilities of process failures. Process hazards analyses (PHAs) have uncovered many of these increased risks. In many cases, this has led to increasing controls with added complexity and cost. The complexity itself can represent a risk. An inherently safer design could replace these designs with less costly maintenance and increased ease of operation while at the same time reducing risks.

The promise of ISD has led the U. S. Congress to introduce bills requiring the application of ISD in every session since 2001, and at least one senior OSHA official has called for increased use of safety in design. The state of New Jersey and Contra Costa County in California currently require the application of ISD.

Because of the benefits of ISD, this paper was written to facilitate its application to existing plants.

INHERENTLY SAFER DESIGN METHODS HAVE MATURED

Many of today's operating plants did not incorporate inherently safer process technology in their design. In addition, inherently safer process design methods have progressed significantly in the three decades since they were first proposed by Trevor Kletz in 1978.

Because it is much easier and less costly to incorporate ISD when designing a new process plant than it is to modify an existing facility, much of the ISD literature has focused on incorporation of ISD during the research, development, and design of new process plants. The time is ripe for ISD reviews for existing plants because most have undergone significant upgrades in process safety information during the past several decades.

Although ISD can enhance the safety of some existing process plants, it is either impractical or not cost effective in others.

COULD YOUR PLANT BENEFIT FROM ISD?

An ISD review could discover opportunities to reduce risks and lower costs. Has new process technology been developed and offers both ISD benefits and economic benefits? Then, life cycle cost/benefit analysis may make ISD of the new process, with subsequent replacement of the existing process, an obvious choice.

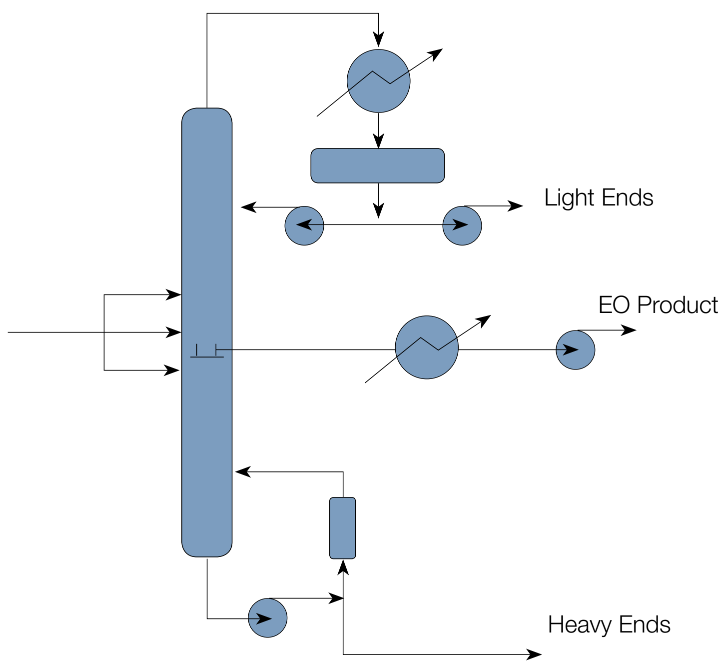

Figure 2. *Inherently safer process*

Four choices with the ISD of new process technology are:

- Modernize the existing plant with the new process technology
- Build a new plant based on the new process technology
- Continue to operate the existing plant with no changes
- Or shut down the existing plant

In either of the first two choices, it is essential that ISD methods should be integrated into the associated design work (Edwards, 2011; Sutton, 2011).

If the decision is made to continue to operate the existing plant, there may still be less costly ISD improvements that can be made to offer potential benefits. This will be addressed later in this paper.

IS YOUR PLANT'S PROCESS SAFETY INFORMATION AN ADEQUATE BASIS FOR AN ISD REVIEW?

Regulatory requirements, as well as recognized and generally accepted good engineering practice, have led to the creation and update of the process safety information of many plants in the US, Europe, Japan and other parts of the world. This process safety information includes adequate and up-to-date documentation of the design and of the basic process control, fire and gas, and safety instrumented systems. This information is supplemented by process hazards reviews, consequence modeling and facility siting studies.

In many cases, ISD may have been considered during initial design and/or baseline PHAs or during subsequent cyclic PHAs. If ISD has been done well, then further consideration of ISD is less likely to result in improvements.

If the existing process safety information for the plant is inadequate, then the first task in an ISD review is to upgrade the plant's process safety information. If upgrading the process safety information includes conducting a process hazards analysis (PHA) and a risk assessment, then the ISD review should be integrated into the PHA and risk assessment [3].

If the process safety information is adequate and if significant hazards exist but ISD does not appear to have been applied, then two ISD reviews are recommended.

TWO LEVELS OF ISD IMPROVEMENTS AND TWO TYPES OF ISD REVIEWS

ISD Screening Review: Major changes in chemistry and/or process configuration (the changes are more costly with existing plants, but big potential improvements may result in both safety benefits and lower operating costs). An example is replacement of a highly toxic process route with a new and much less toxic alternative process with lower operating costs.

ISD Detailed Review: Minor changes in equipment, operating conditions, and process configuration (easiest to do with existing plants, but still potentially significant improvements). For example, upgrades and standardization in gaskets may reduce leaks as well as prevent selection of the wrong gasket from the plant warehouse.

CONDUCT AN ISD SCREENING REVIEW

The ISD Screening Review is intended to identify potentially major process changes with major benefits.

The ISD Screening Review Team should first be grounded in the existing process technology. Then, the team should review the major process hazards and rank the risks. This

TABLE 1. EXAMPLE OF WHAT IF GUIDE WORDS FOR ISD SCREENING REVIEW

Problems with the current technology
Intensification or minimization
Substitution
Attenuation or moderation
Limitation of effects
Simplification
Reconfiguration
Elimination
Supplementation or hybridization
Ensuring dynamic stability

TABLE 2. EXPERIENCE THAT MAY BE NEEDED IN AN ISD SCREENING REVIEW

ISD Review Leader: process safety (plus at least one other relevant expertise)
Process technology and chemistry
Process research and development
Process engineering and plant design
Plant operations
Process dynamics and control
Mechanical engineering

will prepare the team to seek ways to reduce risk.

This review requires the maximum imagination and creativity, so a guided "what if" method using appropriate guidewords is selected for the process. Table 1 lists a few example guidewords. An example question using the guide word "substitute" is: Is it possible to substitute a non-flammable solvent for a flammable solvent?

The ISD review leader should keep the focus on major changes during this review, focusing on brainstorming broad new approaches and capturing, but not exploring, minor issues when they arise. ISD methodology has been clearly documented [1].

The ISD Review leader should have expertise in process safety and at least one of the following areas: technology of the current process and products; process research and development; process engineering and plant design and plant operations. The ISD Screening Review Team should have experience of a typical revalidation or cyclic PHA team, except that in addition, expertise in research and development and in engineering design is very beneficial (Table 2). The best choice of the ISD Screening Review Team is based on the process technology and on the experience and personalities of the team members. At least one member of the team should have a good chemistry background with sound knowledge of the relevant process technology.

If one or more major opportunities are identified, then each of these should be explored in more detail by the team after the initial brainstorming phase is complete. If potentially practical ISD approaches are identified, then these should be documented. These potentially practical ISD approaches should then be evaluated after the screening review by a design team.

CONDUCT AN ISD DETAILED REVIEW

The second type of the ISD Review, the ISD Detailed Review, looks for smaller but potentially worthwhile improvements in the detailed design of the existing facility. It may be desirable to change the team composition somewhat for this detailed review. For example, it is essential to have at least some of the following disciplines present: plant operations, instrumentation, electrical, mechanical, maintenance and quantitative risk assessment expertise. The ideal team composition will depend on the nature of the existing plant.

Here, a "what if"/checklist approach is recommended using a checklist of detailed changes that might offer improvements (Table 3 shows several example guide words and questions [1]). An example of ensuring dynamic stability is reducing inventories (minimization) in the distillation system (i.e., column base, reboiler and reflux drum) without adversely affecting the stability of the system by reducing inventories too much.

Again, after the ISD Team has identified potentially promising ways to make the process inherently safer and/or more user-friendly, these approaches should be turned over to plant management to create one or more design teams to develop and implement the upgrades. In the example of dynamic stability, the design team could conduct dynamic simulations of credible process upsets to the distillation system to evaluate its stability during process operations.

AN EXAMPLE OF SUBSTITUTION AND MINIMIZATION APPLIED TO AN EXISTING PLANT AND ITS SUPPLY CHAIN

In December 1984, the Bhopal tragedy took place in India. A release of Methyl Isocyanate (MIC) in a Union Carbide plant killed approximately 3000 people and injured tens of thousands more. DuPont recognized the potential vulnerability of their U.S. operations to a related MIC incident.

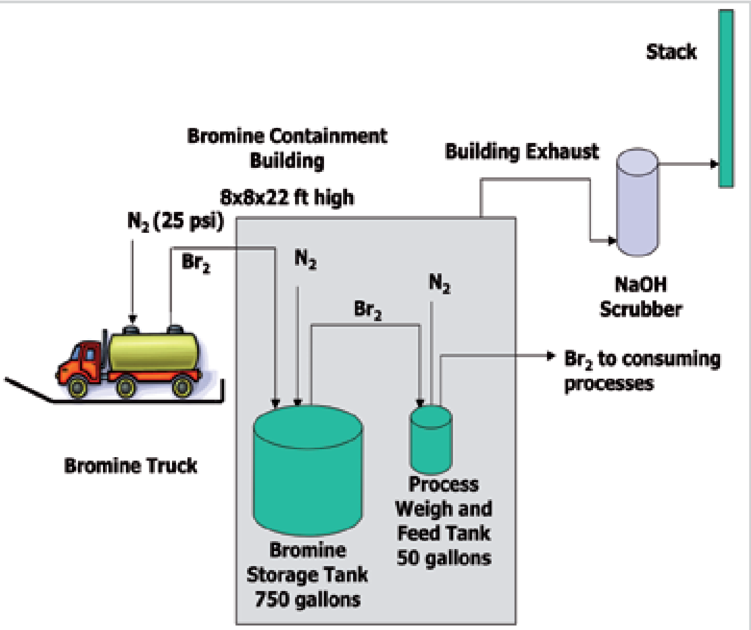

Figure 3. *Original Bromine Supply System*

At the time, DuPont was purchasing MIC from a West Virginia-based supplier and shipping it by a rail car to another plant located near a major metropolitan area over a thousand miles away. There, it was a key ingredient in the manufacture of a very profitable insecticide. Routinely, several million pounds of MIC were maintained in storage on the site at any given time. The Bhopal tragedy immediately raised concerns about the safety of making, shipping and storing MIC in the supply chain for the product.

DuPont's research and development organization responded to the tragedy with a totally new process that utilized the ISD principles of substitution and minimization. An alternative chemistry was developed that allowed for use of a starting material that was significantly less hazardous than MIC; this eliminated the risk of shipping and storing MIC. Alternative reactor technology was then used to convert the new raw material into MIC in situ. The MIC was then immediately reacted and consumed in the next reaction step, limiting the total amount of MIC in in-process inventory to about 10 to 20 pounds.

The need to ship and store MIC was therefore completely eliminated and a roughly five order of magnitude reduction in hazardous material inventory was achieved. This is a great example of the ISD principles of substitution and minimization.

TABLE 3. EXAMPLE OF WHAT IF GUIDE WORDS AND QUESTIONS FOR DETAILED ISD REVIEW

Problems in the existing plant
Making incorrect assembly impossible
Making status clear
Tolerance of misuse
Ease of control
Ensuring dynamic stability
Elimination
Reconfiguration
Can more frequent testing of the SIS improve safety?
Can modification of equipment and/or vessels improve safety?

AN EXAMPLE OF MODERATION AND SIMPLIFICATION FOR INHERENTLY SAFER PRODUCTION OF ETHYLENE OXIDE

Inherently safer designs can be applied to operating plants as evidenced by the work done by Celanese in the area of ethylene oxide manufacture. Ethylene oxide is produced in the vapor phase reaction of ethylene and oxygen. The gaseous product is quenched in a water absorber and then taken to a distillation column where the water is separated and taken out of the bottom ("heavy ends column") and the overhead product is taken to a "light ends column" where the pure ethylene oxide is taken at the bottom and the light ends are removed at the top (see Figure 1).

Since ethylene oxide is a very hazardous chemical, having flammable limits from ~3% to 100% (it has its own oxygen), and being a decomposable and polymerizable chemical through very exothermic reactions, it is not surprising that explosions have occurred in the light ends column where pure ethylene oxide is reboiled. Such explosions happened in a BP Chemicals plant in Antwerp, Belgium, in 1987 where 14 people were injured and in a Union Carbide plant in Seadrift, Texas, in 1991 where 1 person was killed and 32 injured. In both cases, destruction was extensive with total damage to the unit and damage to neighboring units and some damage even outside the plant. Investigation of the latter explosion indicated that in the presence of rust compounds ethylene oxide can violently decompose at lower temperatures than previously estimated.

In order to eliminate the contact of pure ethylene oxide with the hot surfaces provided by a reboiler, the two columns were consolidated into one (see Figure 2). The pure ethylene oxide is removed as a midstream and the light ends are removed overhead. Therefore, only water and heavy ends are in contact with the reboiler, eliminating the potential of ethylene oxide decomposition. In addition, if the column were to lose its heat source and have all the liquid concentrate in the bottom, there would be just a dilute mixture of water and ethylene oxide

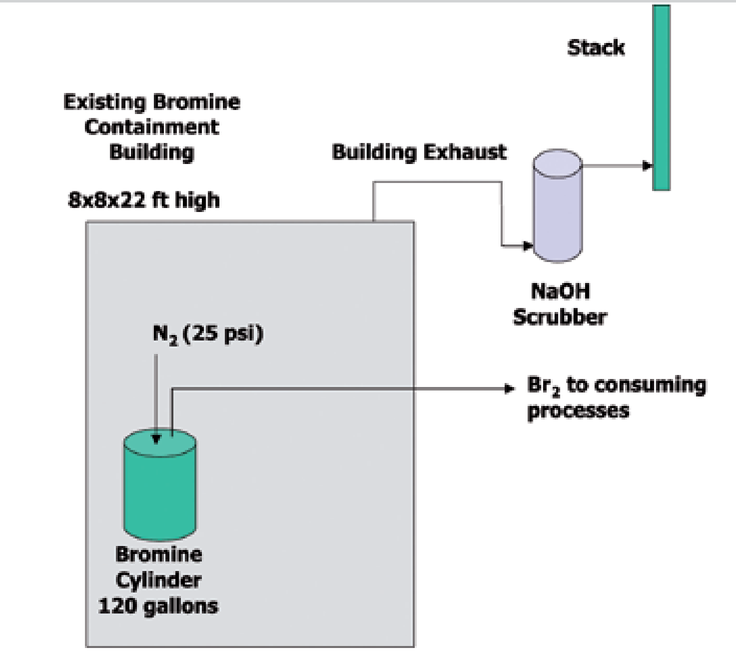

Figure 4. *New Bromine Supply System*

that would not present any danger of decomposition on restart of the column. By eliminating the hazard of runaway exothermic decomposition an inherently safer design was created. A patent has been issued on this inherently safer process.

This is an example of attenuation or moderation, in which the highly reactive ethylene oxide product is handled at a lower temperature by an inherently safer design that avoids contact of concentrated product with a reboiler. This is also an example of simplification, in which two distillation columns are replaced by a single column.

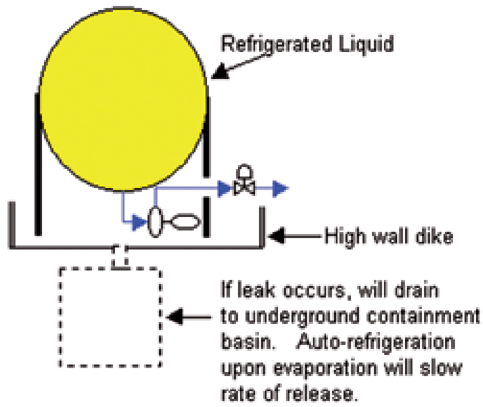

Figure 6. *Dow example of limitation of effects*

ANOTHER EXAMPLE OF AN INHERENTLY SAFER PROCESS THROUGH SUBSTITUTION AND SIMPLIFICATION

A polymer extrusion process at DuPont required the use of a heat transfer fluid. During the process hazards analysis, it was determined that the intended fluid, a combustible liquid, would be operating at a temperature at or near its flash point. To avoid the increased potential for fire or explosion in the event of a loss of containment, an alternative heating medium was selected, one using a non-flammable mixture of propylene glycol and water. This is an example of inherently safer design through substitution.

As an additional benefit, it was determined that the new heat transfer fluid could be used in both "hot" and "tempered" heat transfer systems for the process, allowing simplification of the overall heat transfer system.

AN EXAMPLE OF SIMPLIFICATION AND MINIMIZATION TO REDUCE SOCIETAL RISK

Figures 3, 4 and 5 illustrate that minimization of the inventory of a bromine feed system, along with simplification, led to a dramatic decrease in societal risk at the Rohm and Haas company. Their work is an excellent example of the use of quantitative risk assessment to evaluate alternative processes and their supply chains.

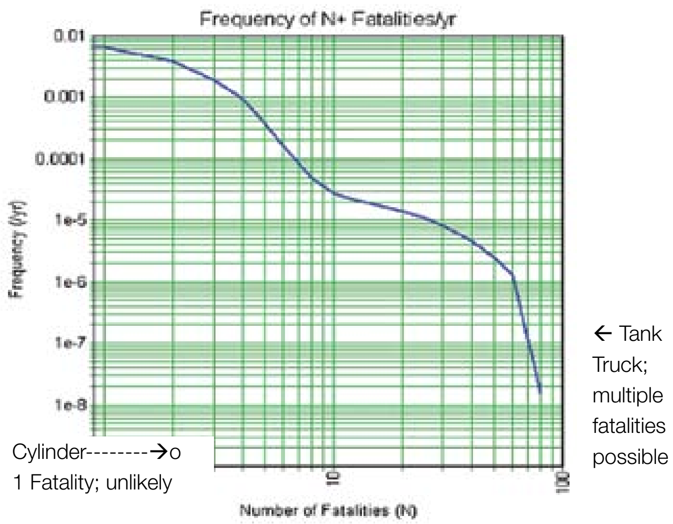

Figure 5. *Societal risk of two Bromine Feed Systems*

AN EXAMPLE OF LIMITATION OF EFFECTS LEADING TO SAFER STORAGE

Figure 6 shows how Dow mitigated the potential hazards from loss of containment of a hazardous liquid by using refrigeration to reduce vapor pressure and specially designed secondary containment to minimize evaporation rate in the event of loss of primary containment.

CONCLUSIONS

There have been numerous recent applications of inherently safer design, resulting in inherently safer processes. However, a significant number of plants operating today may not have considered ISD principles during their creation. The modification of existing plants to become inherently safer can be much more difficult and costly than applying ISD during the conception and design of a new plant. Despite this, there are still opportunities for cost effective application of ISD to some existing plants. ■

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